Structure of charmed baryons and their productions

Atsushi Hosaka, RCNP, Osaka

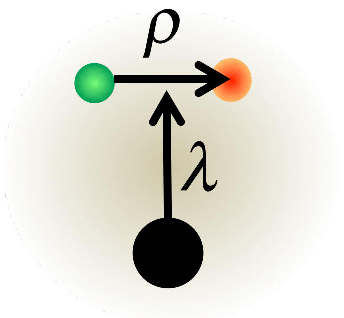
APFB @ Hahndorf, AU, April 7-11

With Noumi, Shirotori, Kim, Sadato, Yoshida, Oka
Motivated by the future JPARC experiments

Contents

1. Introduction
2. Structure: *How **ρλ modes** appear in heavy baryons*
3. Charmed baryon productions

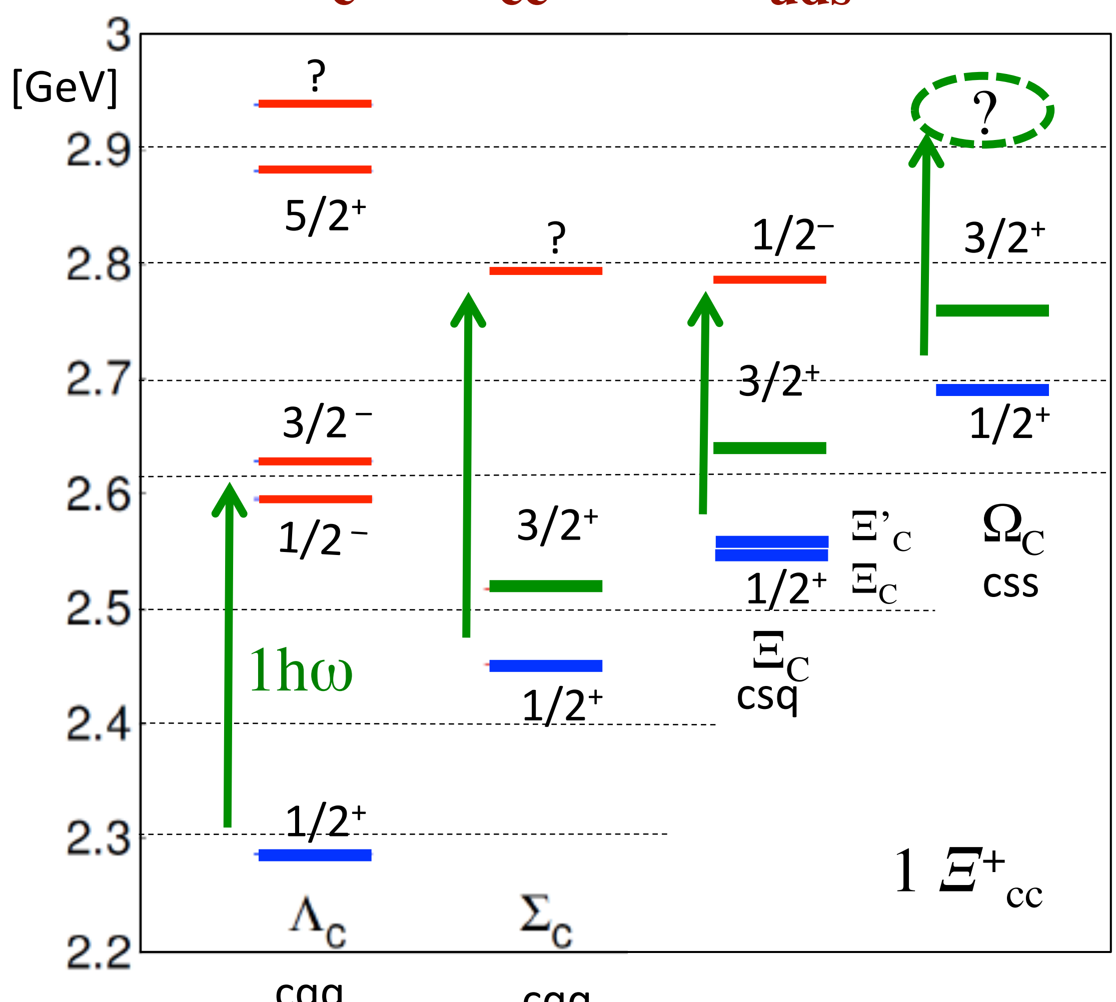
Baryons with heavy quark(s) may disentangle light quark dynamics



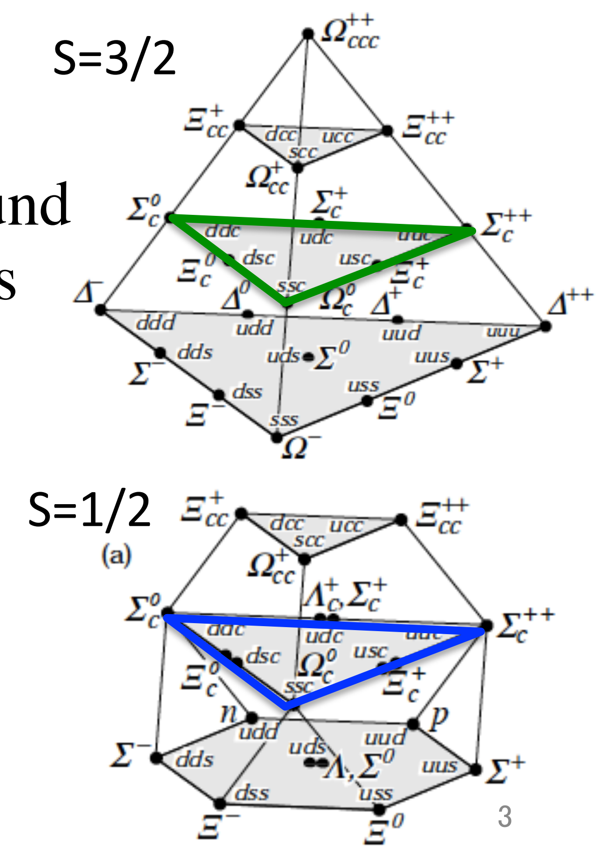
1. Introduction

Charmed baryons

$14_c + 1_{cc} << 80_{uds}$

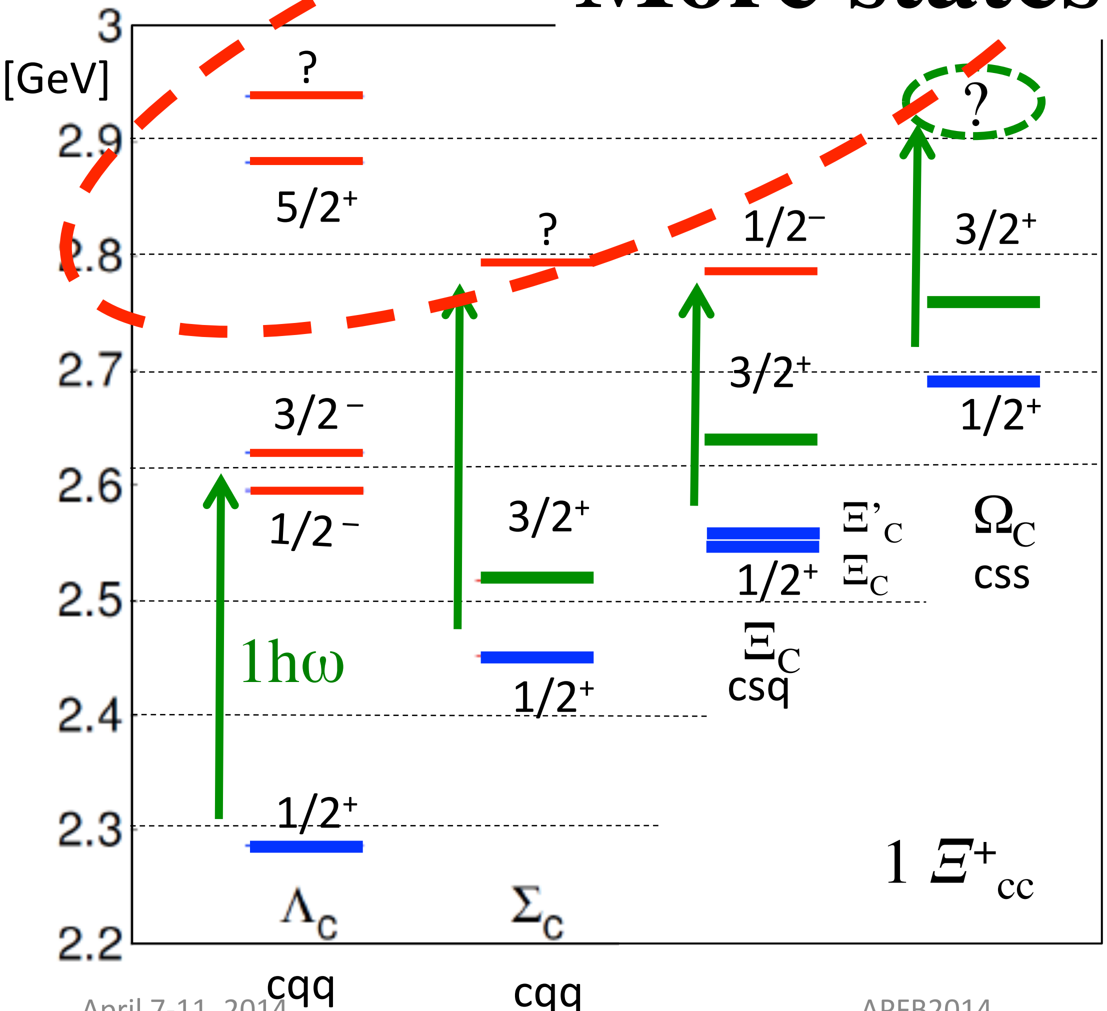


Ground states

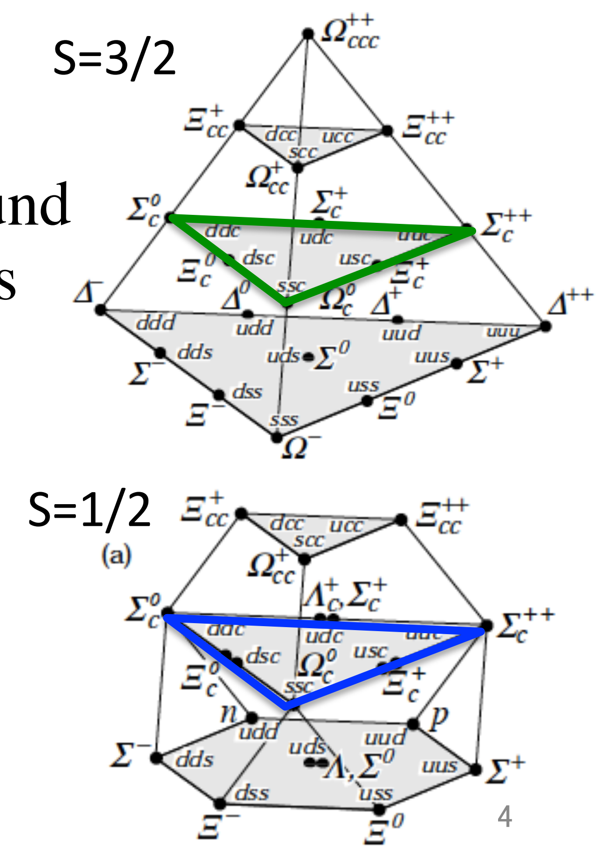


Charmed baryons

$14_c + 1_{cc}$ More states at JPARC



Ground states



What we expect with heavy quarks?

- Heavy spin becomes irrelevant and decouples

→ Heavy quark spin symmetry

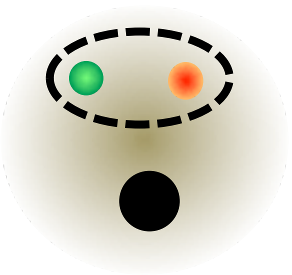
- Flavor SU(3) symmetry is broken

→ Two modes (λ and ρ) may be distinguished

Q + diquark

➔ diquark motions + exitations

diquark spectroscopy

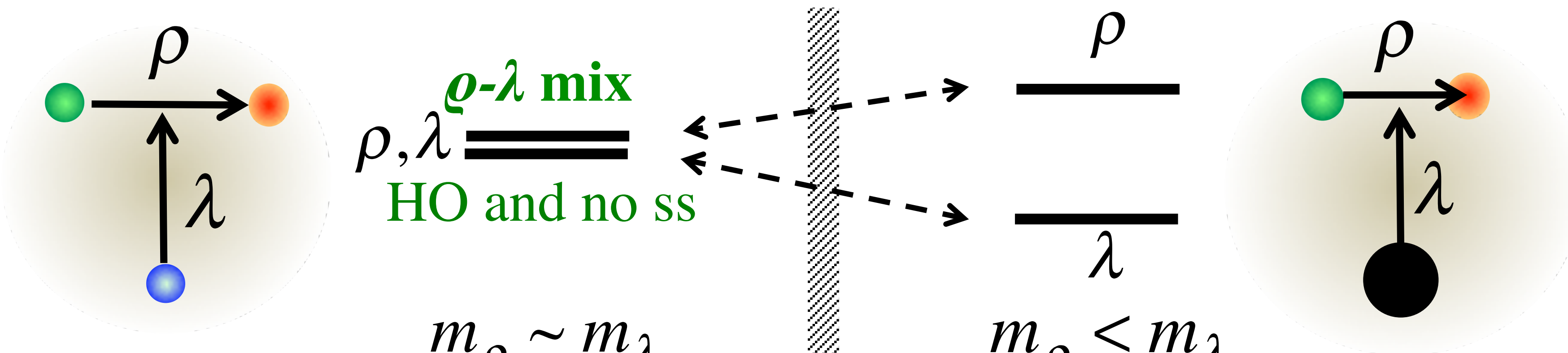


2. Structure:

How ***ρλ modes*** *appear in heavy baryons*

A heavy quark differentiate ***diquark*** motions = modes

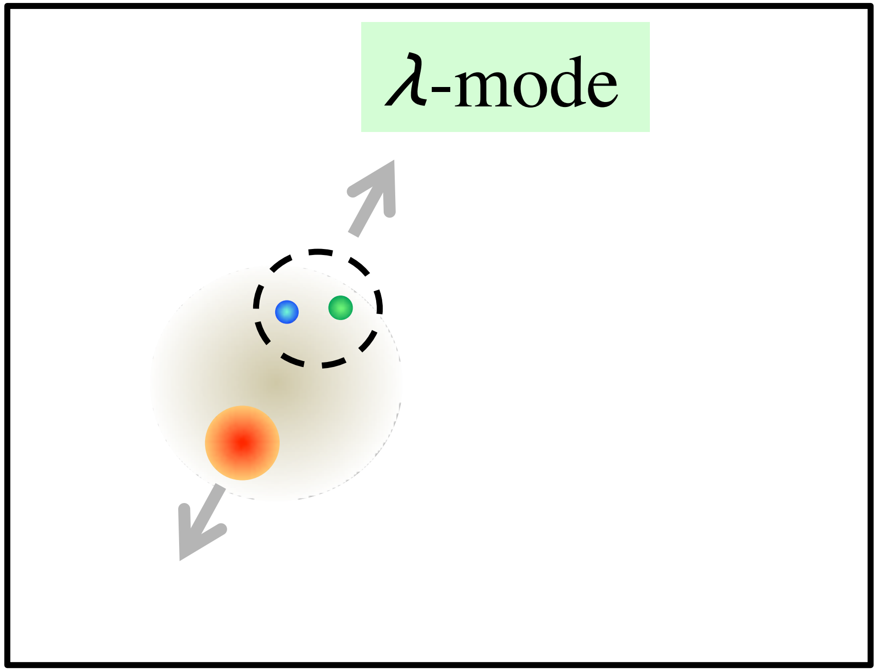
Excitations, ϱ and λ modes get distinct ~ *isotope shift*

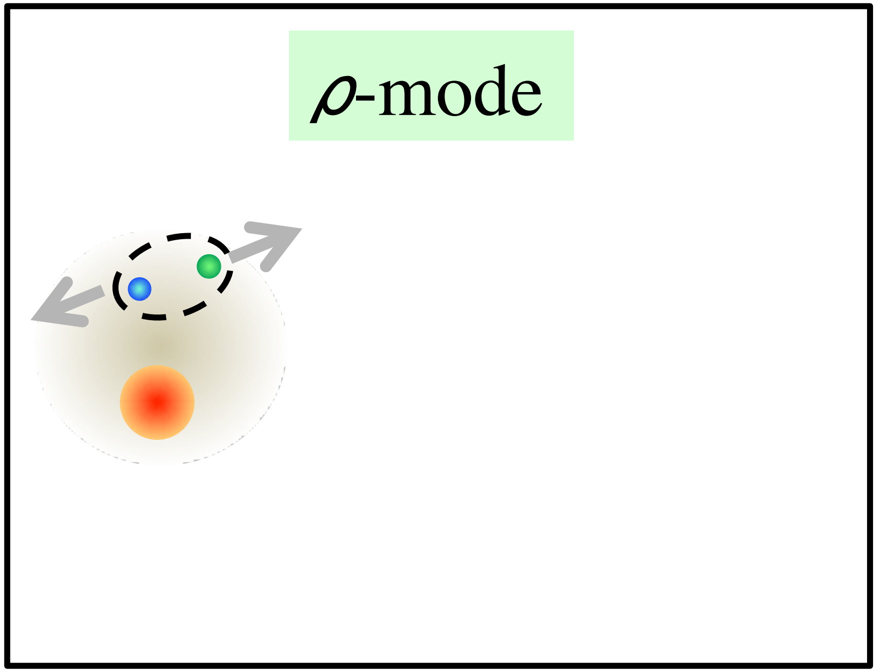


$m_\rho \sim m_\lambda$	$m_\rho < m_\lambda$
$\omega_\rho \sim \omega_\lambda$	$\omega_\rho > \omega_\lambda$

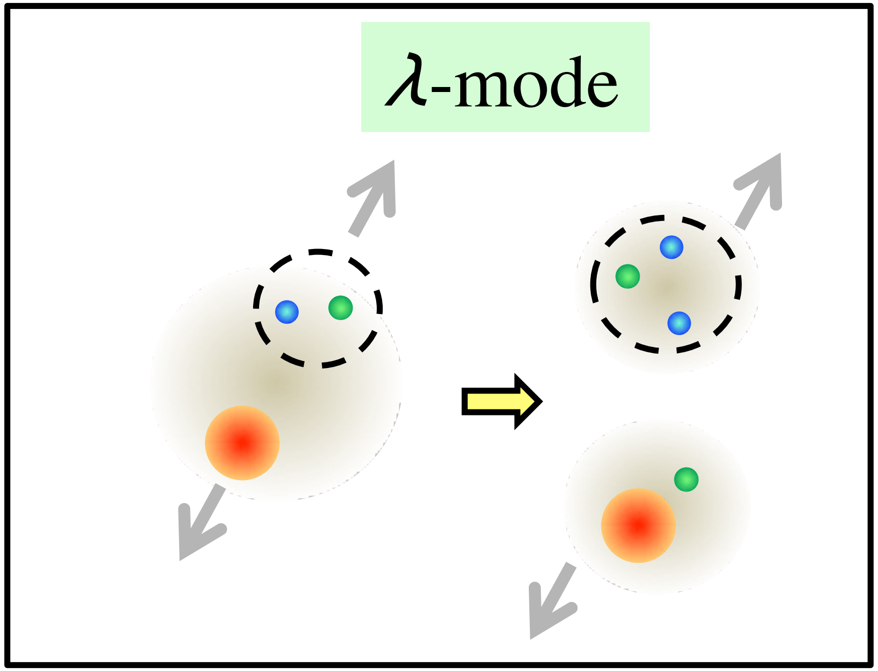
λ mode is more collective

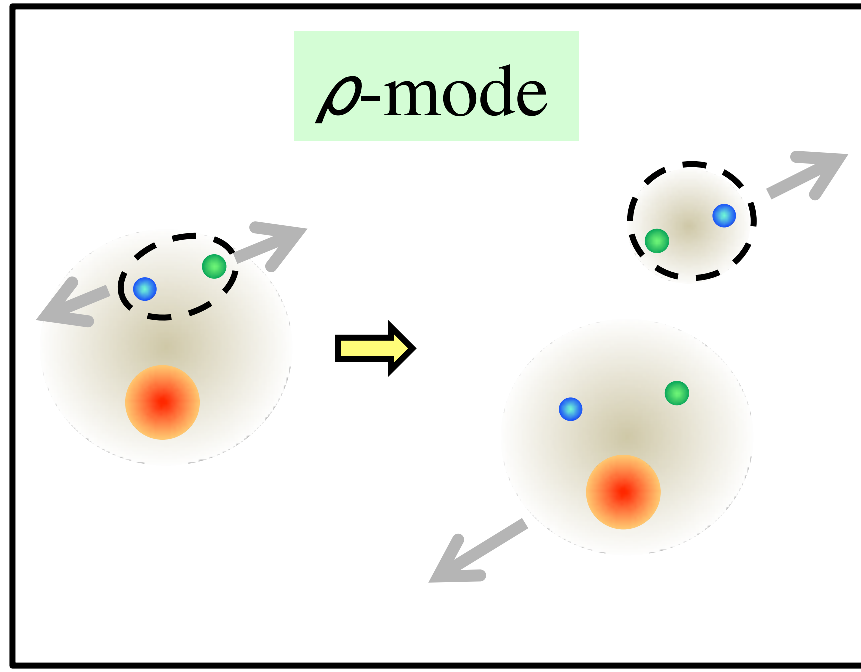
As a consequence -- Decays





As a consequence -- Decays





λ-mode: Q* decays by emitting a heavy meson
ρ-mode: (qq)* decays by emitting a pion

How they appear in excited B_c's
➔ Mixing of the modes

qqQ systems

Quark model calculation
with spin-spin interaction:
Yoshida, Sadato, Hiyama, Oka, Hosaka

Quark model hamiltonian

$$H = \frac{p_1^2}{2m_q} + \frac{p_2^2}{2m_q} + \frac{p_3^2}{2M_Q} - \frac{P^2}{2M_{tot}}$$

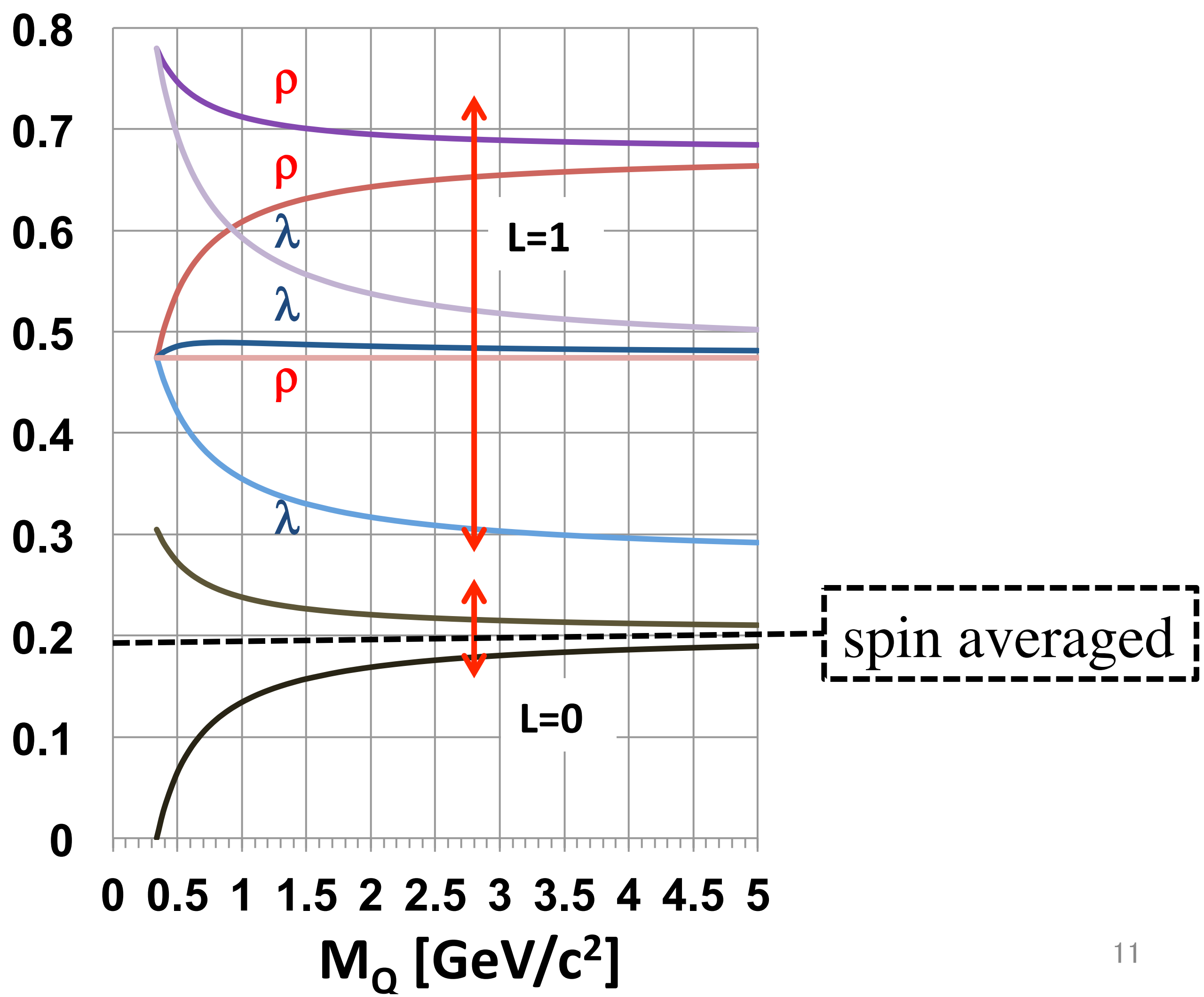
$$+ V_{conf}(HO) + V_{spin-spin}(Color - magnetic) + \dots$$

Solved by the Gaussian expansion method

See how systems change as M_Q is varied

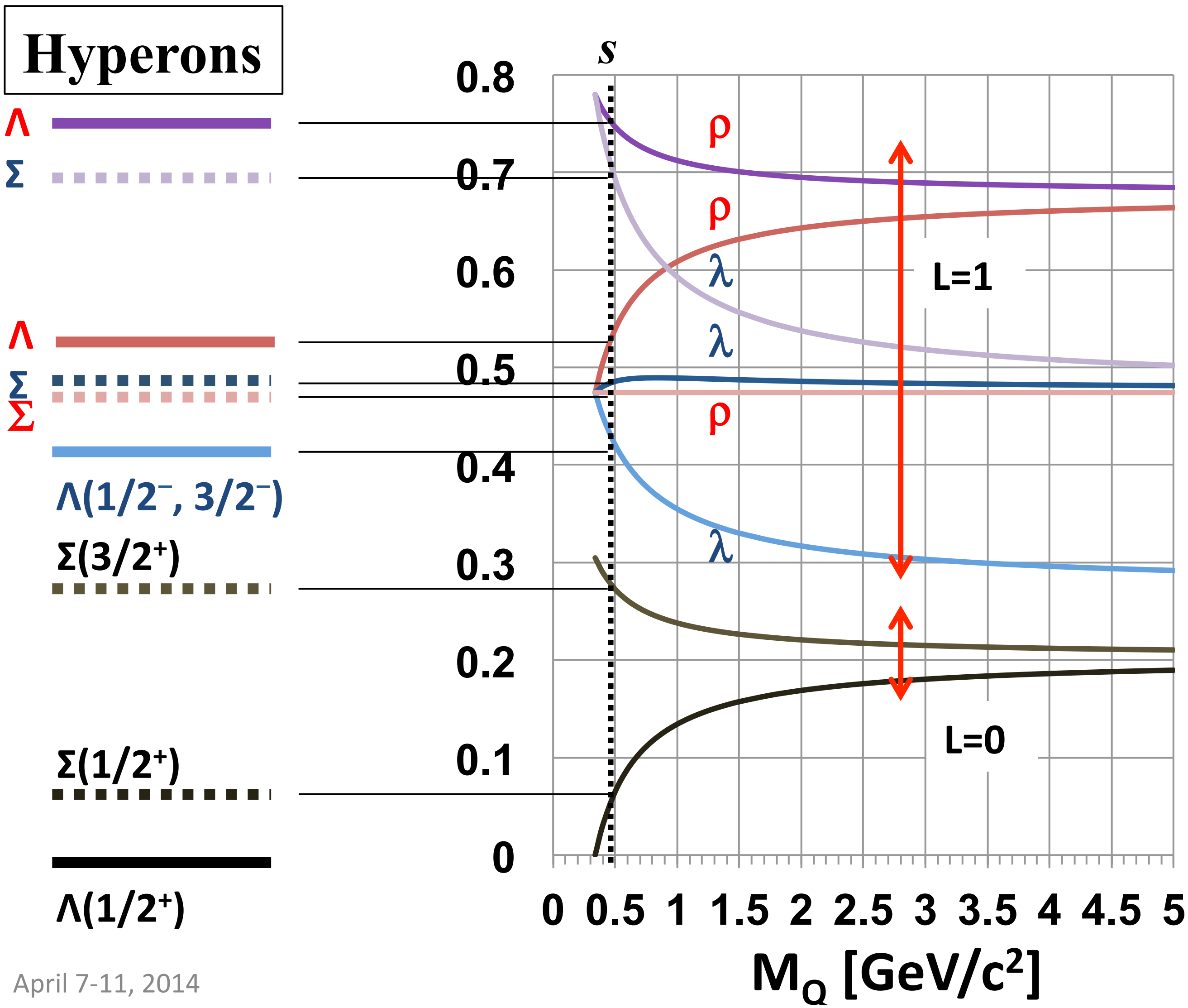
Excitation spectrum

L=1 excited states: spin-spin interaction



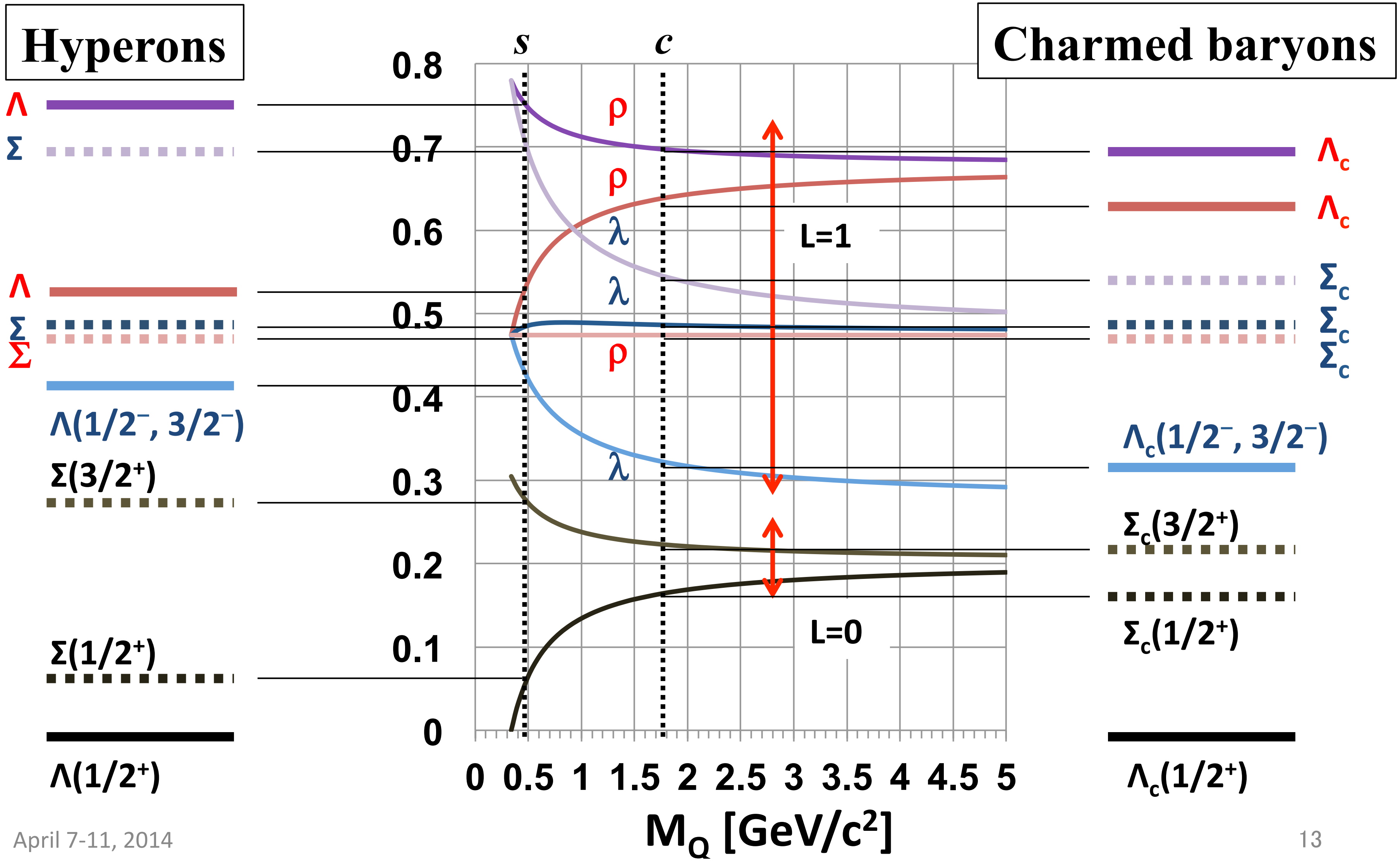
Excitation spectrum

L=1 excited states: spin-spin interaction

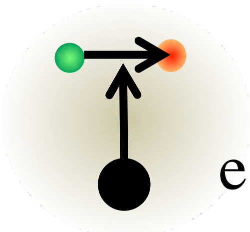


Excitation spectrum

L=1 excited states: spin-spin interaction



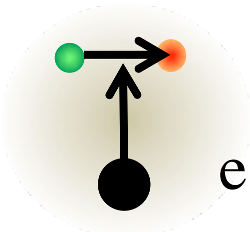
Wave function



Mixing of $\psi = c_\lambda |l_\lambda = 1\rangle + c_\rho |l_\rho = 1\rangle$

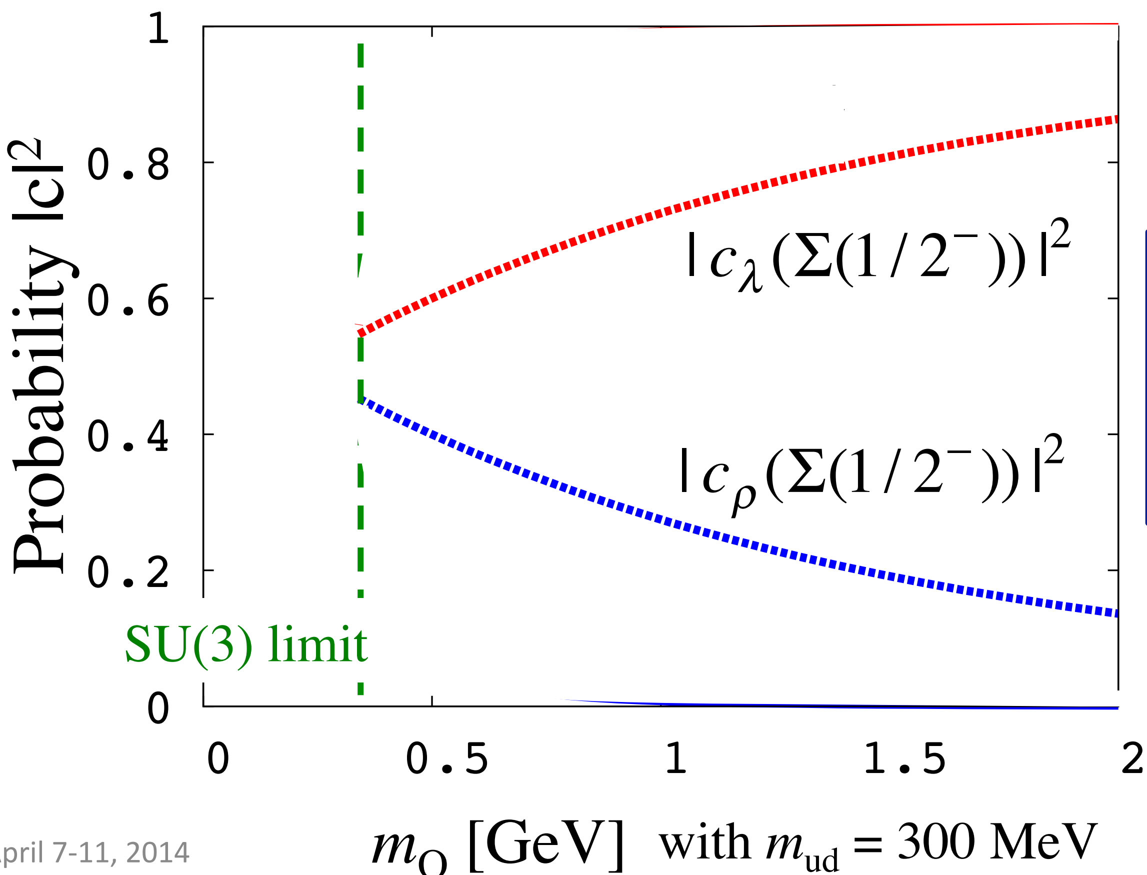
e.g. λ-mode dominant state: How much the other mode mixes?

Wave function



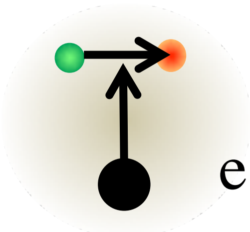
Mixing of $\psi = c_\lambda |l_\lambda = 1\rangle + c_\rho |l_\rho = 1\rangle$

e.g. λ-mode dominant state: How much the other mode mixes?



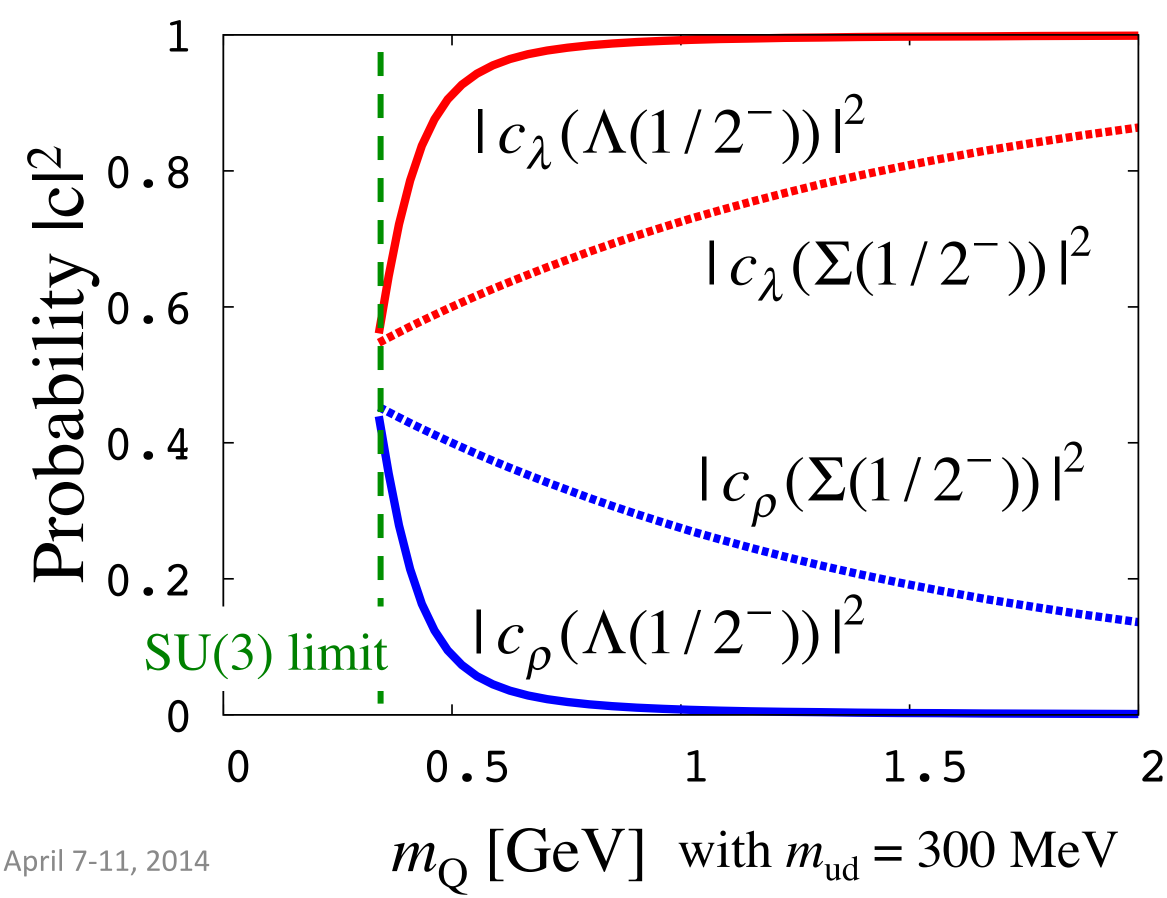
Substantial amount of mixing in Σ

Wave function



Mixing of $\psi = c_\lambda |l_\lambda = 1\rangle + c_\rho |l_\rho = 1\rangle$

e.g. λ-mode dominant state: How much the other mode mixes?



Λ_c^* is almost pure λ mode
➔
Reflect more diquark nature

see Talk by Shirotori

3. Charmed baryon productions

Strategies:

Consider D^* (Vector meson) prodution

At high energies: Forward peak → t-channel dominant

See the next figure

- <u>**Absolute values**</u>

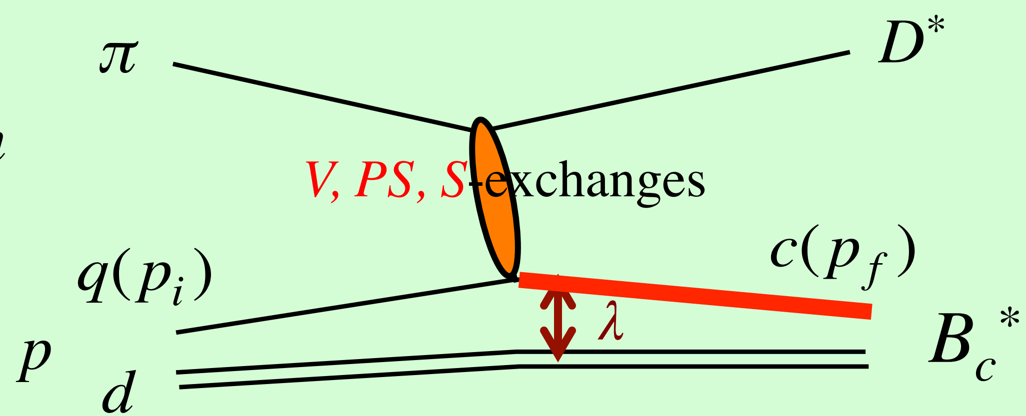
  Regge for the estimation of charm vs strange

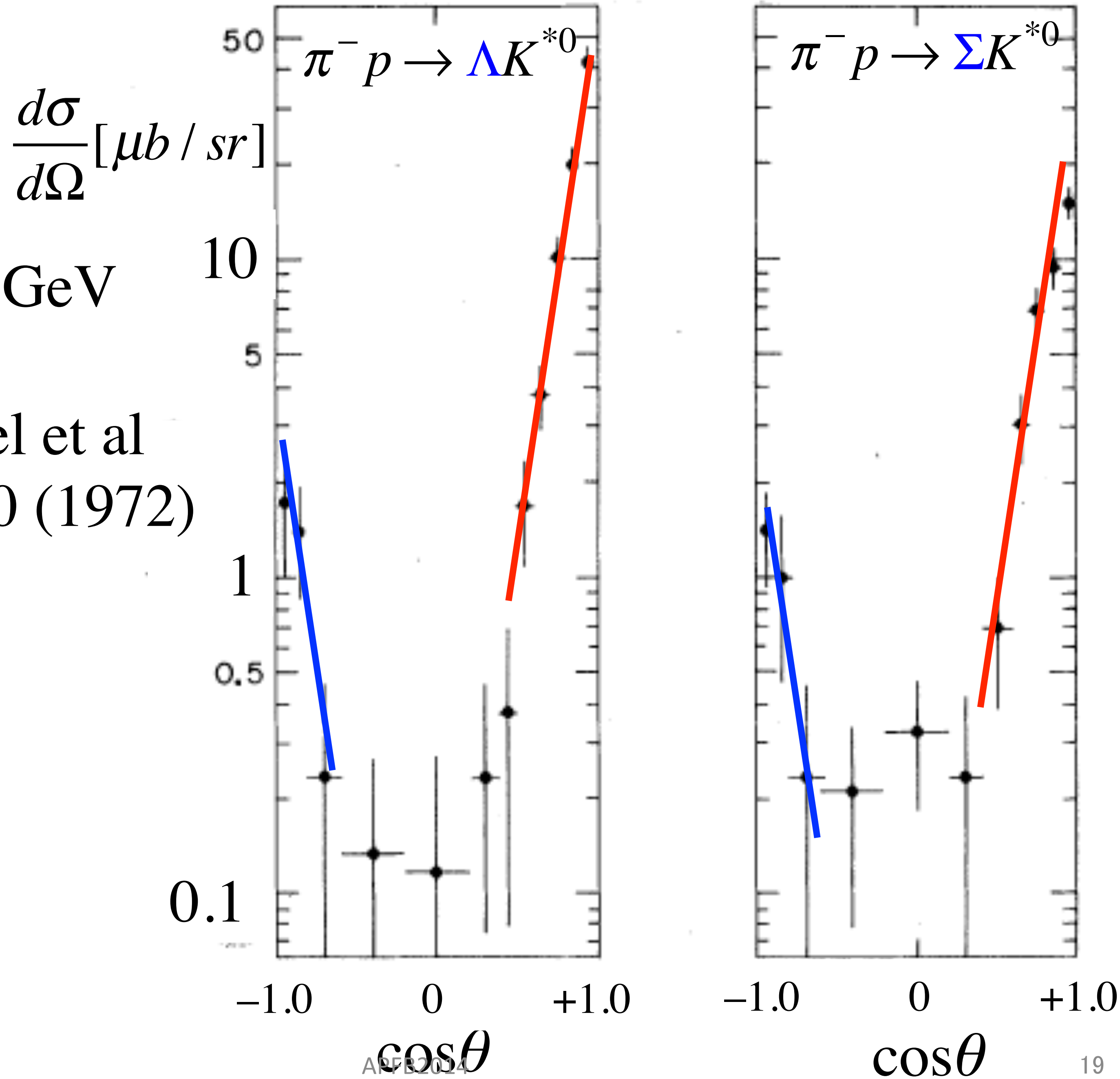
- <u>**Relative ratios**</u> of transitions to various B_c^*

  One step process in a *Qd* model

Pion-induced reaction

$\pi + p \rightarrow D^* + B_c^*$



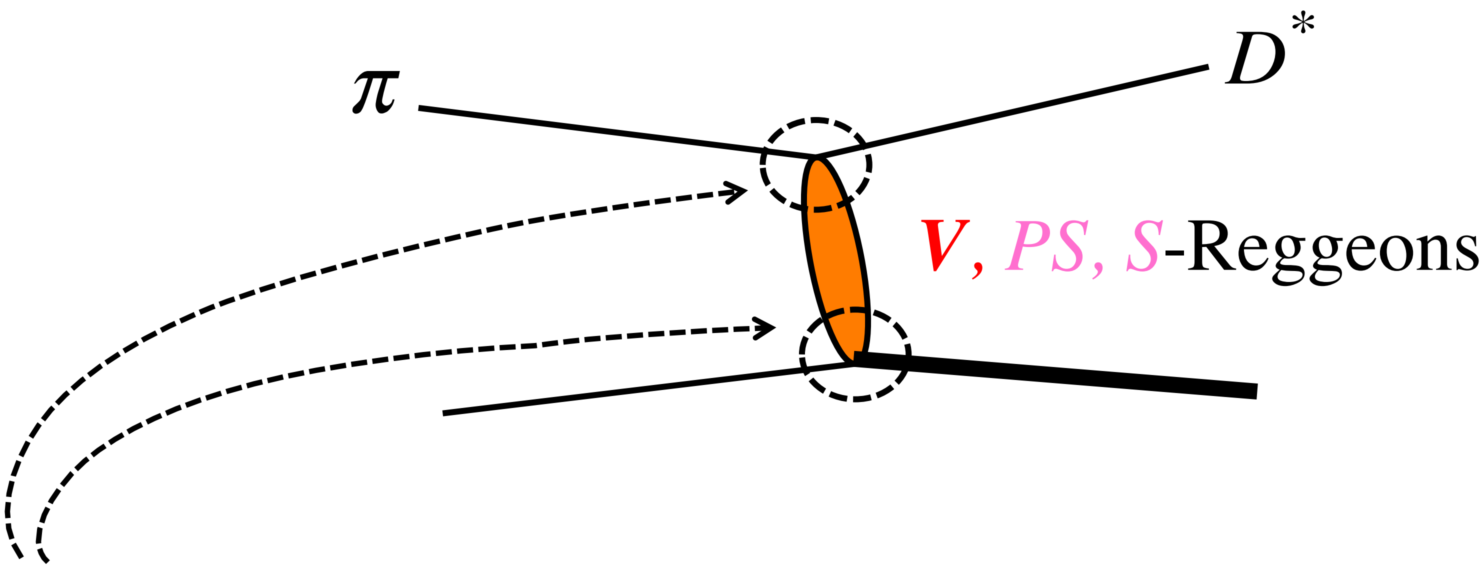


$p_{\pi,\,\mathrm{Lab}} = 4.5$ GeV

D.J. Krennel et al
PRD6, 1220 (1972)

Absolute values

Regge method with couplings fixed at strangeness

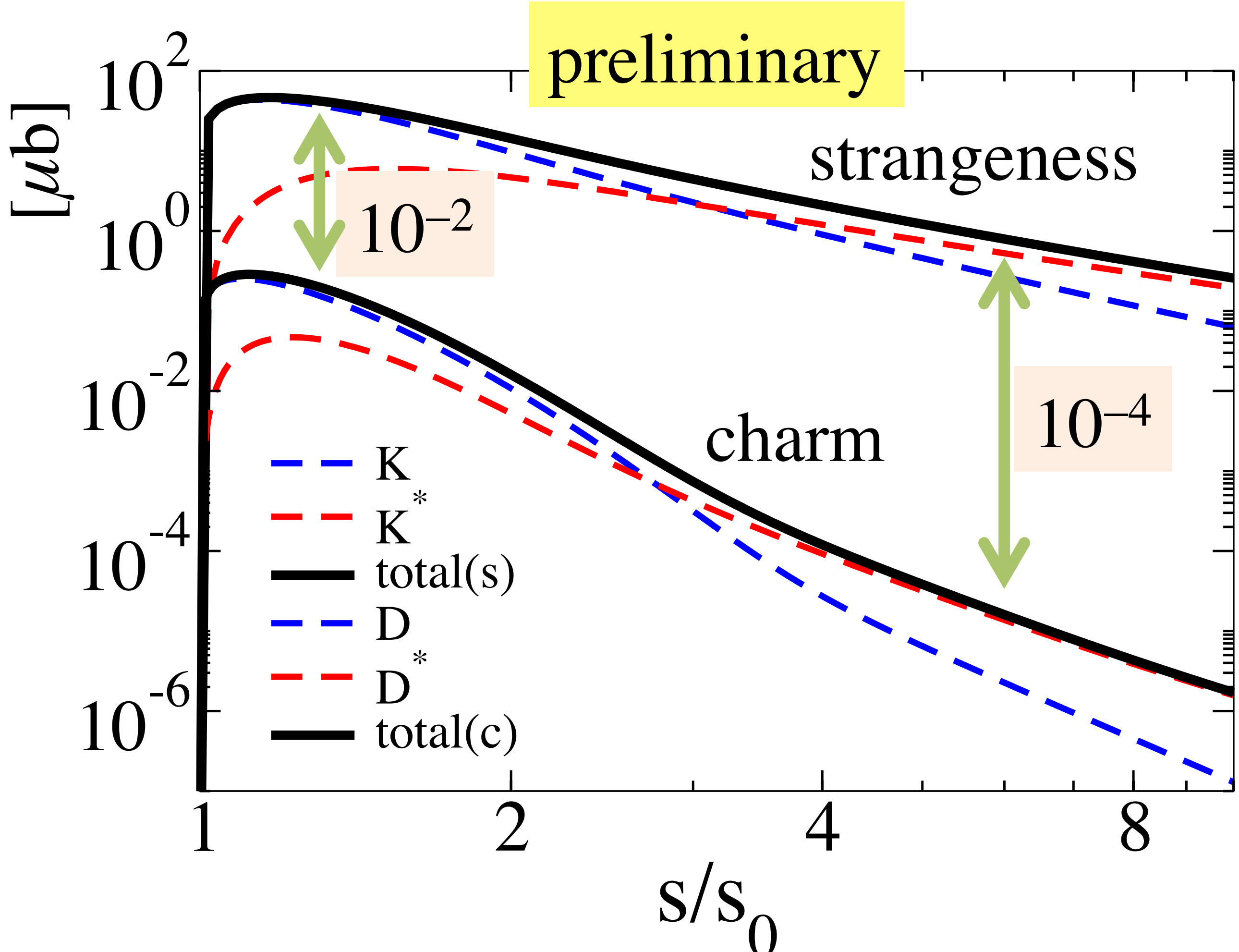


- Coupling structure is determined by effective Lagrangians
- Propagators are replaced by the Regge's

$$\frac{1}{t-m_{K^*}^2} \rightarrow \mathcal{P}_{regge}^{K^*} = \left(\frac{s}{s_0}\right)^{\alpha_{K^*}(t)-1} \frac{1}{\sin(\pi\alpha_{K^*}(t))} \frac{\pi\alpha'_{K^*}}{\Gamma(\alpha_{K^*}(t))}.$$

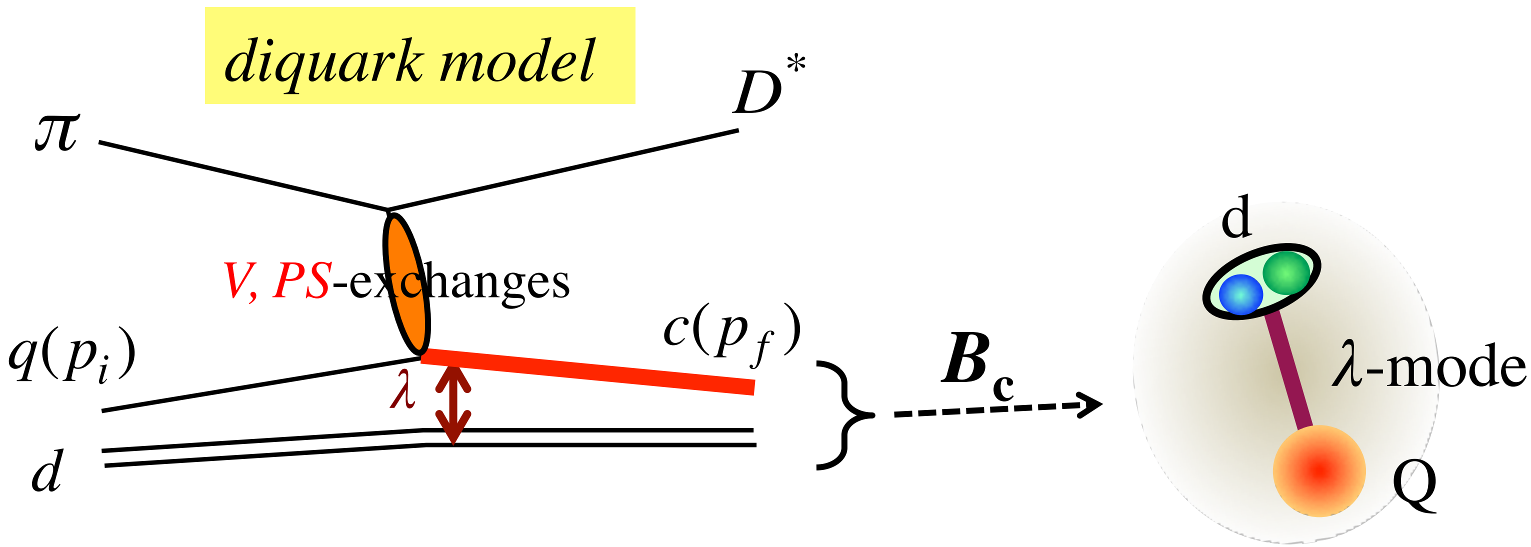
Sang-Ho Kim (RCNP)

Regge method with couplings fixed at strangeness



Charm/strangeness productions: $10^{-2} \sim 10^{-4}$

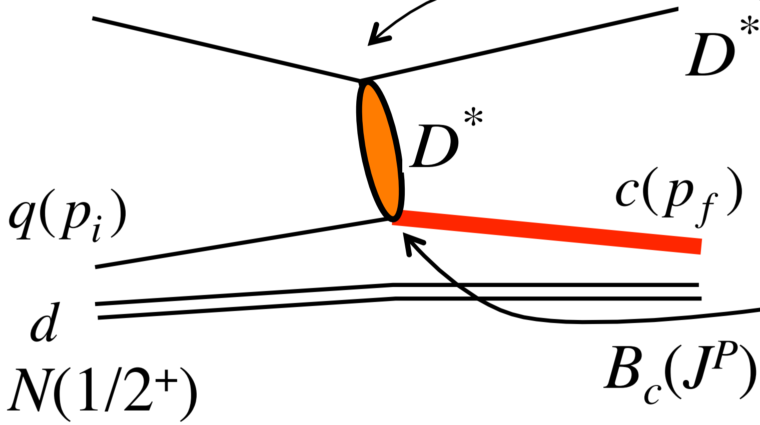
Relative ratios to various B_c



- Single step $q \rightarrow Q$: λ modes are excited
- V, PS exchanges for D^* productions with various B's of $l_\lambda = 0, 1, 2$ (18 baryons)
- Estimate forward scattering amplitudes

Single-step $qd \to Qd$ reaction

Example of V-exchange



$$\mathcal{L}_{\pi D^* D^*} = f\epsilon_{\mu\nu\alpha\beta}\partial^\mu \pi \partial^\nu D^\alpha D^\beta$$

$$\mathcal{L}_{D^* NB} = g\bar{c}\gamma^\mu D_\mu q$$

$$t \sim 2fgk^0_{D^*}\vec{k}_\pi \times \vec{e}\cdot \vec{J}_{fi}\frac{1}{q^2 - m^2_{D^*}} \qquad \vec{q}_{eff} = \frac{m_d}{m_d + m_q}\vec{P}_N - \frac{m_d}{m_d + m_c}\vec{P}_B$$

$$\vec{J}_{fi} = \int d^3x\,\varphi^\dagger_f \left[\frac{\vec{p}_f}{m_c + E_c} + \frac{\vec{p}_i}{m_q + E_q} + i\vec{\sigma}\times\left(\frac{\vec{p}_f}{m_c + E_c} - \frac{\vec{p}_i}{m_q + E_q}\right)\right]\varphi_i\, e^{i\vec{q}_{eff}\cdot\vec{x}}$$

V-exchange at forward

$$t_{fi} \sim \left(\frac{P_B}{2(m_c + m_d)} - 1\right) k^0_{D^*}k_\pi \langle B_c | \vec{e}_\perp \cdot \vec{\sigma} e^{i\vec{q}_{eff}\cdot\vec{x}} | N\rangle \frac{1}{q^2 - m^2_{D^*}}$$

Matrix elements

$$V: \quad \langle B_c | \vec{e}_\perp \cdot \vec{\sigma} e^{i\vec{q}_{eff}\cdot\vec{x}} | N \rangle$$

Transverse

$$PS: \quad \langle B_c | \vec{e}_{//} \cdot \vec{\sigma} e^{i\vec{q}_{eff}\cdot\vec{x}} | N \rangle$$

Longitudinal

$= \quad (\text{Geometric}) \times (\text{Dynamic})$

CG coefficients

Dynamical part ~ radial integral

GS

$$\langle B_c(\text{S-wave})|\vec{e}_\perp \cdot \vec{\sigma} e^{i\vec{q}_{eff}\cdot\vec{x}}|N(\text{S-wave})\rangle_{radial} \sim 1 \times \exp\left(-\frac{q_{eff}^2}{4A^2}\right)$$

Excited states

$$\langle B_c(P\text{-wave})|\vec{e}_\perp \cdot \vec{\sigma} e^{i\vec{q}_{eff}\cdot\vec{x}}|N(\text{S-wave})\rangle_{radial} \sim \left(\frac{q_{eff}}{A}\right)^1 \times \exp\left(-\frac{q_{eff}^2}{4A^2}\right)$$

$$\langle B_c(D\text{-wave})|\vec{e}_\perp \cdot \vec{\sigma} e^{i\vec{q}_{eff}\cdot\vec{x}}|N(\text{S-wave})\rangle_{radial} \sim \left(\frac{q_{eff}}{A}\right)^2 \times \exp\left(-\frac{q_{eff}^2}{4A^2}\right)$$

Transitions to excited states are not suppressed

Results

Charm $k_{\pi}^{CM} = 2.71$ [GeV] , $k_{\pi}^{Lab} = 16$ [GeV]

$l=0$	$\Lambda_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{3}{2}^+)$					
	1.00	0.02	0.16					
$l=1$	$\Lambda_c(\frac{1}{2}^-)$	$\Lambda_c(\frac{3}{2}^-)$	$\Sigma_c(\frac{1}{2}^-)$	$\Sigma_c(\frac{3}{2}^-)$	$\Sigma'_c(\frac{1}{2}^-)$	$\Sigma'_c(\frac{3}{2}^-)$	$\Sigma'_c(\frac{5}{2}^-)$	
	0.90	1.70	0.02	0.03	0.04	0.19	0.18	
$l=2$	$\Lambda_c(\frac{3}{2}^+)$	$\Lambda_c(\frac{5}{2}^+ -)$	$\Sigma_c(\frac{3}{2}^+)$	$\Sigma_c(\frac{5}{2}^+)$	$\Sigma'_c(\frac{1}{2}^+)$	$\Sigma'_c(\frac{3}{2}^+)$	$\Sigma'_c(\frac{5}{2}^+)$	$\Sigma'_c(\frac{5}{2}^+)$
	0.50	0.88	0.02	0.02	0.01	0.03	0.07	0.07

Strange $k_{\pi}^{CM} = 1.59$ [GeV], $k_{\pi}^{Lab} = 5.8$ [GeV]

$l=0$	$\Lambda(\frac{1}{2}^+)$	$\Sigma(\frac{1}{2}^+)$	$\Sigma(\frac{3}{2}^+)$					
	1.00	0.067	0.44					
$l=1$	$\Lambda(\frac{1}{2}^-)$	$\Lambda(\frac{3}{2}^-)$	$\Sigma(\frac{1}{2}^-)$	$\Sigma(\frac{3}{2}^-)$	$\Sigma'(\frac{1}{2}^-)$	$\Sigma'(\frac{3}{2}^-)$	$\Sigma'(\frac{5}{2}^-)$	
	0.11	0.23	0.007	0.01	0.01	0.07	0.067	
$l=2$	$\Lambda(\frac{3}{2}^+)$	$\Lambda_c(\frac{5}{2}^+ -)$	$\Sigma(\frac{3}{2}^+)$	$\Sigma(\frac{5}{2}^+)$	$\Sigma'(\frac{1}{2}^+)$	$\Sigma'(\frac{3}{2}^+)$	$\Sigma'(\frac{5}{2}^+)$	$\Sigma'(\frac{5}{2}^+)$
	0.13	0.20	0.007	0.01	0.004	0.02	0.038	0.04

Summary

- ρ and λ modes are separately studied (Isotope shift) better in Λ than in Σ
- ρ-modes may open di-quark spectroscopy
- Systematic study in strangeness is important

- Production in one step process is studied
- Higher excited (Λ) states may be produced as many as the ground states

NSTAR 2015 Workshop

Osaka, Japan, May 25 (mon) – 28(thu)

Florida State University (1994), Jefferson Lab (1995)
INT in Seattle (1996), George Washington University (1997)
ECT* in Trento (1998), Jefferson Lab (2000)
Mainz (2001), Pittsburg (2002), LPSC in Grenoble (2004)
Florida State University (2005), University of Bonn (2007)
Beijing (2009), Jefferson Lab (2011), Valencia (2013)

Diquarks

$$d_S = qq(S=0), \quad d_A = qq(S=1)$$

ss attractive ss repulsive

B_C

$$\Lambda(1/2^+, gs) = \left|[d_S c]\right\rangle, \quad \Sigma(1/2^+, gs) = \left|[d_A c]\right\rangle$$

$$\Lambda(1/2^-, \lambda) = c_\lambda \left|[d_S c], l_\lambda = 1\right\rangle + c_\rho \left|[d_A c], l_\rho = 1\right\rangle$$

$$\Sigma(1/2^-, \lambda) = c_\lambda \left|[d_A c], l_\lambda = 1\right\rangle + c_\rho \left|[d_S c], l_\rho = 1\right\rangle$$

N

$$p(1/2^+, gs) = c_S \left|[d_S u]\right\rangle + c_A \left|[d_A u]\right\rangle$$

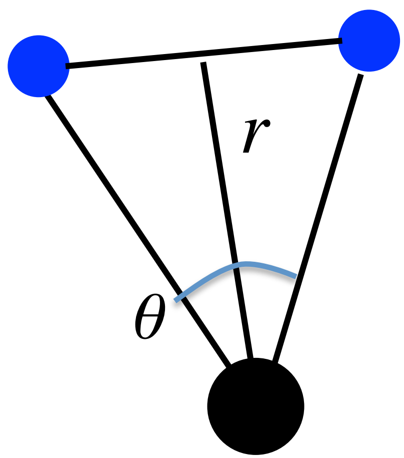
SU(6) quark model: $c_S = c_A$

Strong scalar diquark: $c_S > c_A$

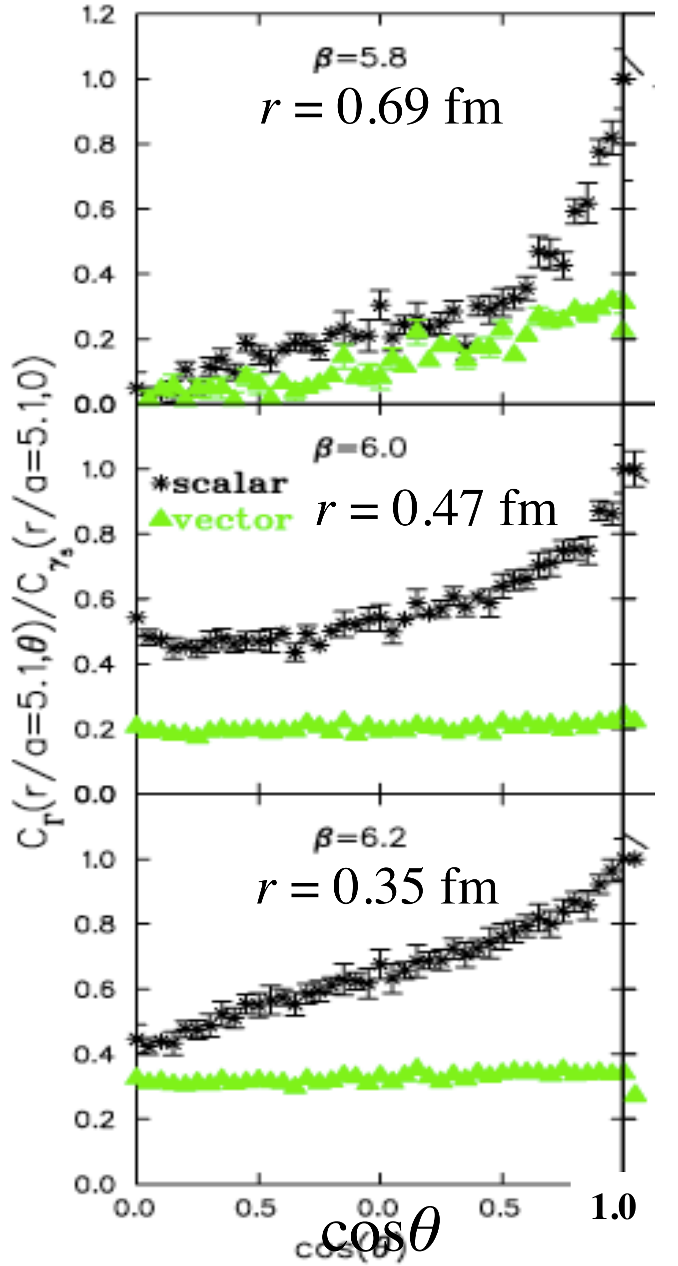
Diquark correlations
enhance Λ, while suppress Σ productions

Density correlations

Alexandrou, deForcrand, Lucini
PRL 97, 222002 (2006)



Good diquark
Bad diquark



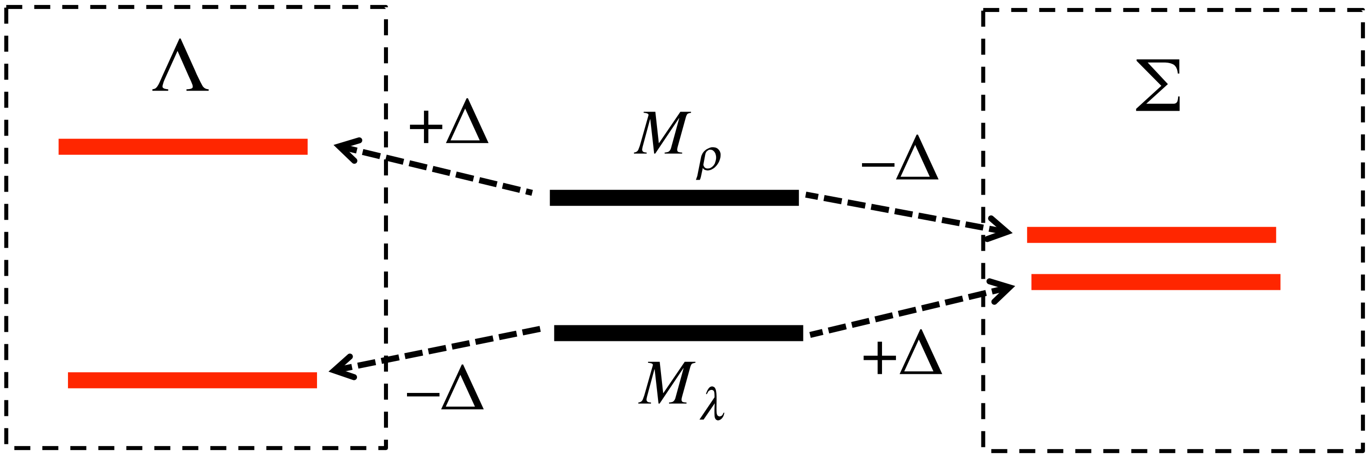
Indicates significant attraction
between quarks in good diquark pair

$$d_S = qq(S=0), \quad d_A = qq(S=1)$$

$$\Lambda(1/2^-,\lambda) \;=\; \text{dominant}\, \left|[d_S c], l_\lambda = 1\right\rangle \;+\; \left|[d_A c], l_\rho = 1\right\rangle$$

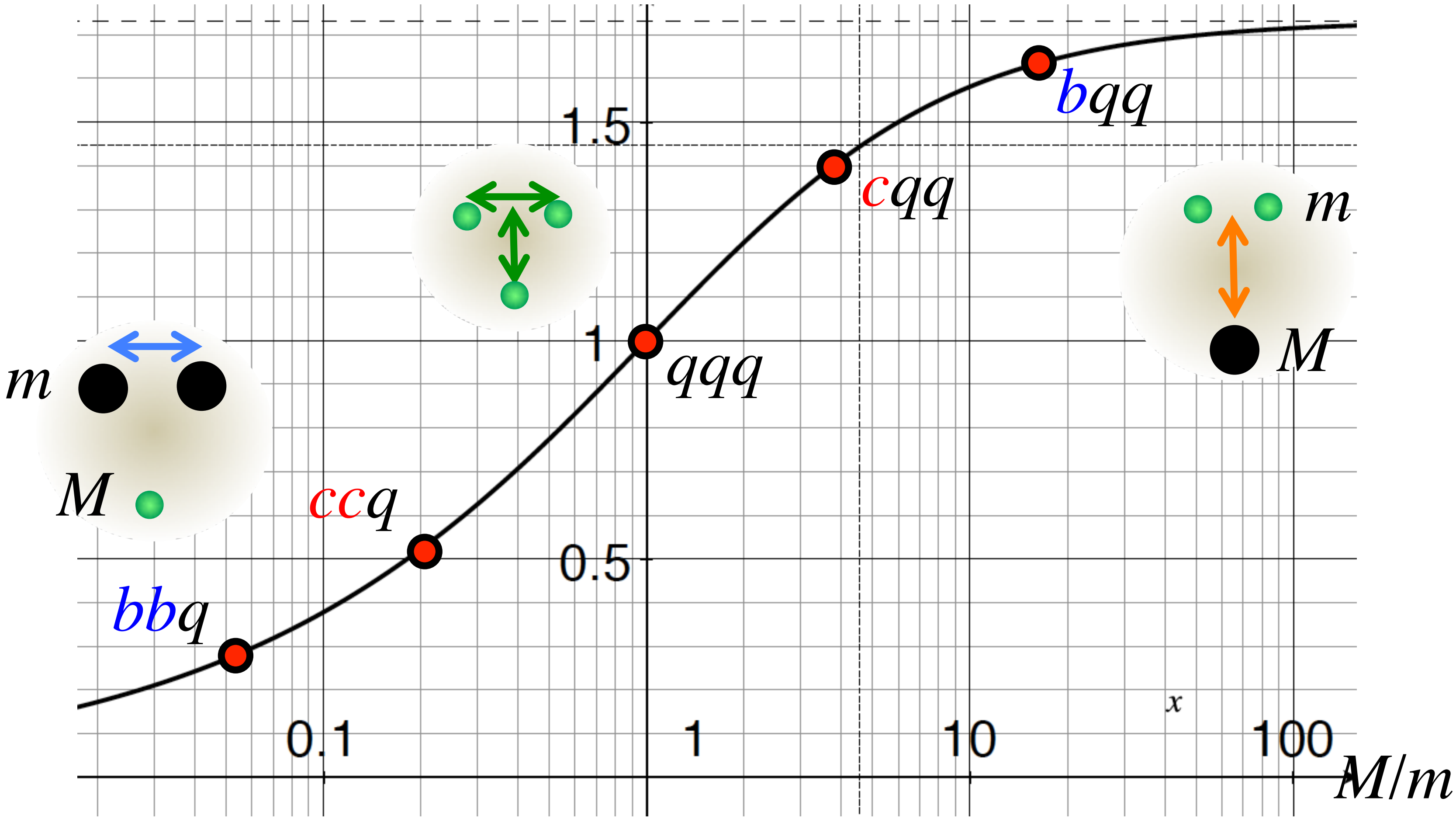
$$\Sigma(1/2^-,\lambda) \;=\; \text{dominant}\, \left|[d_A c], l_\lambda = 1\right\rangle \;+\; \left|[d_S c], l_\rho = 1\right\rangle$$

$$H = \begin{pmatrix} M_\rho & 0 \\ 0 & M_\lambda \end{pmatrix} \rightarrow \begin{pmatrix} M_\rho \pm \Delta & \delta \\ \delta & M_\lambda \mp \Delta \end{pmatrix}$$

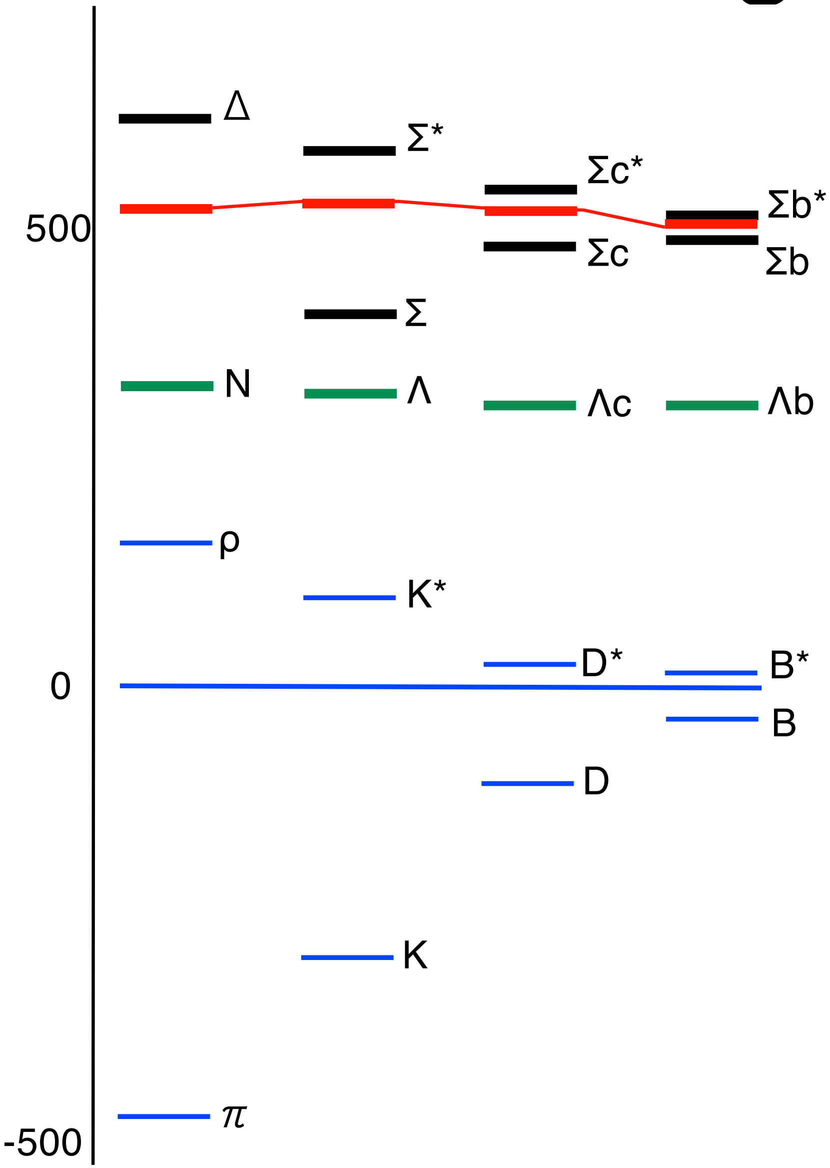


Spectrum

$$\frac{\omega_\lambda}{\omega_\rho} = \left[\frac{1}{3}\left(1 + \frac{2m}{M}\right)\right]^{1/2} = \left[\frac{1}{3}(1+2x)\right]^{1/2}$$



Interesting systematics



bad diquark
with spin-spin
of (qq)-Q

(qq)-Q
S=1, 1/2

addition of
one more q
with good qq

[qq]-Q
S=0, 1/2

spin-spin
subtracted

q-qbar
S=1/2, 1/2